BREAKDOWN PROCESSES IN LASER-TRIGGERED SWITCHING*

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Abstract

Time-resolved optical diagnostics of coaxial laser-triggered (Nd:YAG, 1.06μ) nitrogen filled spark gap operation have shown breakdown to result from a laser assisted streamer propagating from the laser fireball to the opposite electrode. Streak photography shows that the streamer precursor of the breakdown channel initially proceeds across the gap at about 10^8 cm/sec, but slows to about 2×10^7 cm/sec as it advances in the focal cone to regions of lower laser intensity. The laser interaction with the streamer produces a relatively uniform, resistive channel which is then rapidly heated ohmically until the gap voltage collapses, and intense continuum emission is produced. When the streamer transit time is greater than the laser pulse length two distinct regions can be detected in the arc channel: one laser assisted, showing the abrupt appearance of continuum luminosity, and the other not laser assisted, appearing much like a weakly overvolted breakdown event.

Introduction

We report here the results of a recently completed study of laser-triggered electrical breakdown in nitrogen,[1] and we present the first direct evidence for the role of a laser assisted streamer in the triggering process. The study specifically investigated the basic physical processes important in the laser triggered breakdown event. Such a study is significant both because of the role of laser triggered switches in pulse power technology, and because of the unique advantages the technique offers for studying electrical breakdown in general.

The study included experiments involving several different spark gap triggering configurations, all of which are shown in Figure 1. The configurations will be referred to as: Type 1, coaxial laser beam focused on or near one electrode; Type 2, transverse laser beam focused in the mid-gap region; Type 3, coaxial laser beam focused within a recess in one electrode; and Type 4, coaxial laser beam focused in mid-gap, and not striking any electrode. Results from each of these configurations were compared to breakdown events caused by overvolting the spark gap. Primary emphasis was placed on understanding the processes occurring in the Type 1 geometry.

Apparatus

The laser triggered switching study was carried out on a 50 ohm system consisting of a length of RG-8/U coaxial cable as the energy storage element, a low inductance spark gap assembly with optical access

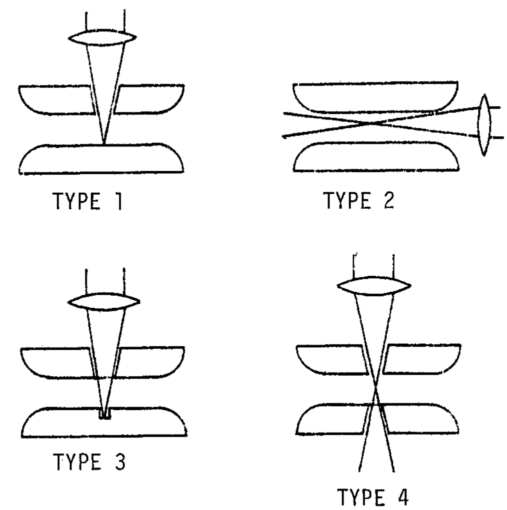

Figure 1. Spark gap triggering configurations. Types 1 and 3 were triggered with about 10 mJ of laser energy, Types 2 and 4 with about 100 mJ

from several directions, and a 50 ohm load. The spark gap spacing was 5 mm, the pressure 800 Torr, and stainless steel, uniform field electrodes were used. Optical diagnostics included a Hammamatsu Model C979 streak camera with microchannel plate intensifier and SIT vidicon or 35 mm camera for image acquisition. Additionally, a PAR optical multichannel analyzer enabled spectral data to be acquired with 5 ns resolution. The laser which served as the trigger was a Quanta-Ray Model DCR-1A Nd:YAG laser with unstable resonator, 15 ns pulse width, and up to 100 MW power. Generally the output was attenuated to 1-10 MW. Standard current measurements were also made.

Breakdown Model

Based on the experimental observations which will be presented later, we propose the following model of laser triggered breakdown in the Type 1 geometry. The tightly focused beam from the trigger laser rapidly heats the metal surface of the target electrode, explosively evaporating material which is subsequently heated and ionized. This high density plasma serves as a seed to promote heating of the insulating spark gap fill gas, probably through an inverse-Bremsstrahlung process.[2,3] The relatively dense plasma formed near the target electrode surface then shields itself from the applied electric field, creating a field enhancement near the tip of the plasma, where electrons readily ionize the gas molecules and extend the plasma into the gap as a streamer. The ionization rate at the streamer tip is enhanced both by the high electric field, and by the optical field of the

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14. ABSTRACT
Time-resolved optical diagnostics of coaxial laser-triggered (Nd:YAG, 1.06~) nitrogen filled spark gap operation have shown breakdown to result from a laser assisted streamer propagating from the laser fireball to the opposite electrode. Streak photography shows that the streamer precursor of the breakdown channel initially proceeds across the gap at about 108 em/sec, but slows to about 2 x 107 em/sec as it advances in the focal cone to regions of lower laser intensity. The laser interaction with the streamer produces a relatively uniform, resistive channel which is then rapidly heated ohmically until the gap voltage collapses, and intense continuum emission is produced. When the streamer transit time is greater than the laser pulse length two distinct regions can be detected in the arc channel: one laser assisted, showing the abrupt appearance of continuum luminosity, and the other not laser assisted, appearing much like a weakly overvolted breakdown event.

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laser beam. The interaction with the laser beam takes the form of a direct ionization rate enhancement due to inverse-Bremsstrahlung absorption. Some distance from the target electrode the laser interaction with the streamer ceases, due either to the cessation of the laser pulse, the lower laser intensity away from the focus, or because the streamer branches around the entrance aperture to reach the opposite electrode. At the point that the laser interaction ceases, the breakdown process proceeds similarly to an overvolted breakdown process. After the streamer has crossed the gap, the gap is bridged by a thin weakly conducting filament which is then rapidly heated by ohmic effects. The laser-guided filamentary channel, having a diameter determined by the diameter of the focused laser beam, is much smaller than that of a non-laser-assisted channel, making heating more rapid. A similar, but less detailed model was first proposed by Guenther and Bettis.[4]

Experimental Evidence

The first optical evidence of laser interaction in the breakdown process was observation of the uniform, abrupt onset of intense continuum emission along nearly the entire length of the arc channel, as shown in Figure 2a. As shown in Figure 2b, distinctly different features are observed in an overvolted breakdown process.[4] In contrast to the self breakdown process, the Type 1 laser triggered process became luminous with continuum emission simultaneously along the entire gap length, with the exception of a small area near the laser entrance electrode. A glow discharge appeared in the vicinity of the laser entrance electrode emitting light in the C-B electronic band of the nitrogen molecule. The intense continuum emission later filled this space, moving inwards from both ends in a manner similar to that observed in overvolted breakdown. The similarity of the emission characteristics in this portion of the gap to those of an overvolted breakdown process are unmistakable. The fraction of the gap length occupied by the glow region was dependent on several factors, including laser power and charging voltage, varying directly with the delay to breakdown. With increasing delay time, resulting from either lower charging voltage, or decreased laser power, the length was roughly constant at 1 mm until a delay time exceeding the laser pulse length was reached, whereupon the length of the glow region increased, approximately proportionally to the excess delay.

The results of the optical diagnostics were supported by current measurements. In the self breakdown case the current was observed to have a stepwise growth characteristic, displaying one value for the duration of the glow, (approximately 50% of the final value) then rising to the higher value as the arc was forming. In the case of laser triggered breakdown, the current rose in a single step to the full value. Figures 3a, and 3b display the current characteristics for these two cases.

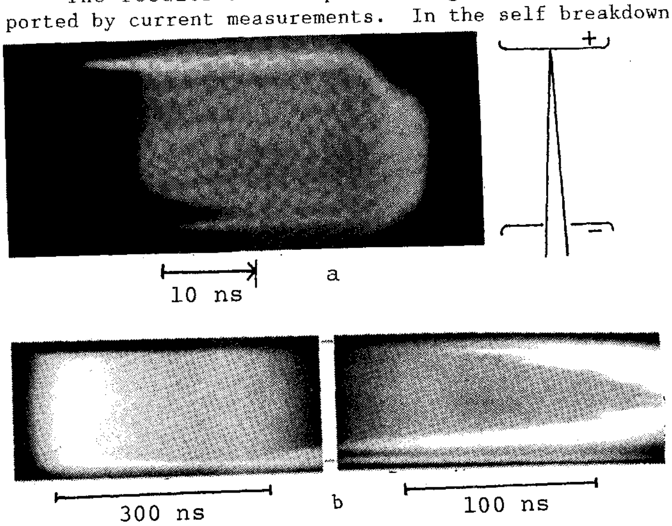

Figure 2. In a), Type 1 laser triggered breakdown, in b), overvolted breakdown (after Doran).

The most direct demonstrations of the presence of an initial streamer process in the breakdown phase were the streak photographs obtained with very high sensitivity in the streak camera, and with limited

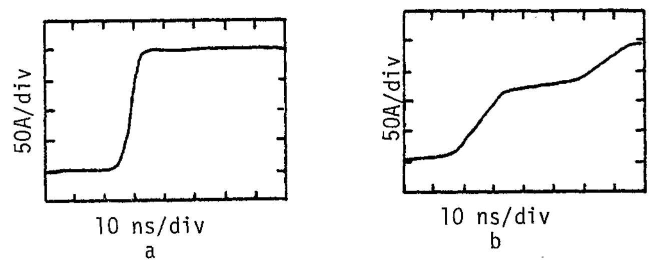

Figure 3. Typical current traces for a) Type 1 laser triggered breakdown, and b) weakly overvolted breakdown.

current duration to prevent flooding of the streak camera electron optics. Figure 4 clearly shows the streamer crossing the gap and leaving an initial trail which was subsequently heated through an ohmic process to form the arc channel. The most surprising feature of this photograph is that the streamer appeared to slow from $\simeq 2\times10^8$ cm/sec to $\simeq 3\times10^7$ cm/sec in its passage across the gap. This slowing is contrary to the conventional behavior of streamers, but can be explained by the proposed laser interaction with the streamer. As the streamer progressed across the gap the laser illumination became less intense due to the larger laser beam diameter away from the focus, and the decay of the laser pulse. Exact correlation of the instantaneous streamer velocity with laser intensity was very difficult due to mode beating effects in the laser which caused large intensity fluctuations on short (<1ns) time scales.

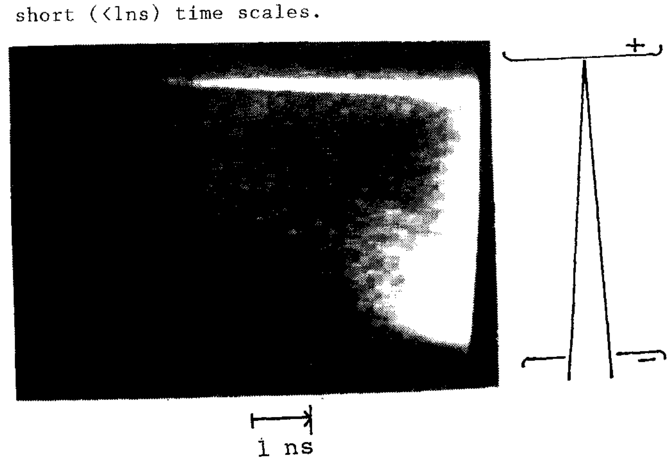

Figure 4. Streak photograph of initial streamer process while utilizing high gain on MCP, and SIT vidicon to record the image. This photograph was taken from the face of the monitor which displayed the stored digitized image.

Experiments with the Type 2 triggering geometry, in which the trigger laser beam was incident and focused transversely in the mid-gap region, not

striking any electrode surfaces, revealed a breakdown process remarkably similar to overvolted breakdown. In this geometry, interaction between the laser and the formative spark channel was minimized due to the transverse introduction of the laser beam into the gap. As shown in Figure 5, despite the relatively dense, hot plasma formed in the middle of the gap, the breakdown proceeded generally along the lines of a self breakdown. The glow stage was apparent, and growth of the highly ionized channel progressed from the electrode surfaces to the middle of the gap.

Type 3 triggering further elucidated the role of the laser beam and the streamer process in the formation of the arc channel. In this triggering geometry the laser was incident coaxially, thus the entire length of the arc channel was exposed to the laser beam as in the Type 1 geometry. Additionally,

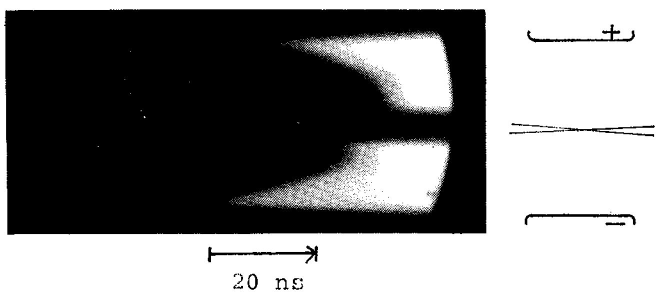

Figure 5. Streak photograph of electrical breakdown in the Type 2 triggering geometry. A stop in the center of the slit blocked intense light from the triggering plasma.

the plasma formed on the target electrode was free to illuminate the intra-gap region virtually to the same degree as in the Type 1 geometry. Therefore, the optical creation of excited states was approximately the same as in Type 1 triggering. The significant difference was that in this Type 3 geometry the laser plasma was formed in a field-free region, where a streamer process could not be initiated until the plasma reached roughly the plane of the electrode surface. In fact, the plasma did not reach this surface until nearly the end of the laser pulse. Thus, negligible interaction of a streamer with the laser was expected to occur, and a process much like self breakdown was anticipated. If, on the other hand, optically excited states were important, the breakdown should have appeared similar to that of Type 1 laser triggering. Figure 6 demonstrates that the breakdown process did indeed proceed in much the same manner as an overvolted breakdown. This is further proof for the claim that the breakdown is dominated by a direct laser interaction with the streamer, rather

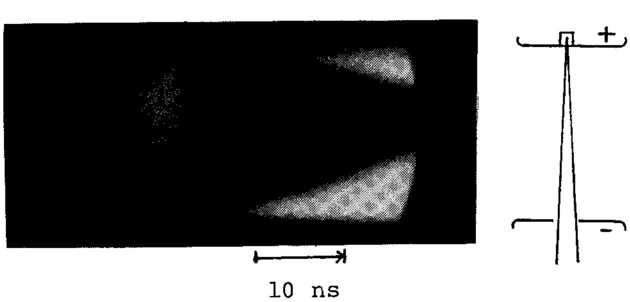

Figure 6. Streak photograph of electrical breakdown in the Type 3 triggering geometry.

than an interaction of the streamer with optically excited states left in the path of the streamer prior to its traverse.

Conclusive evidence for the laser-streamer interaction was found in experiments involving Type 4 triggering, and in Type 1 triggering with laser power well above the threshold for triggering. Several spots of intense luminosity were formed, apparently at hot spots in the focussed laser beam.[6] This was a result of heating of the incipient arc channel by the laser. The local plasmas so formed were opaque to the laser beam as evidenced by the immediate cessation of growth in a particular plasma spot when another spot formed upstream. The association of these spots with the ionization caused by electrical breakdown is demonstrated by the photographs in Figure 7. At zero charging voltage the laser plasma expanded smoothly from the electrode surface into the gap. As the voltage was increased, one or more bright spots were formed in the channel after the passage of a streamer. There did not appear to be any decrease in current

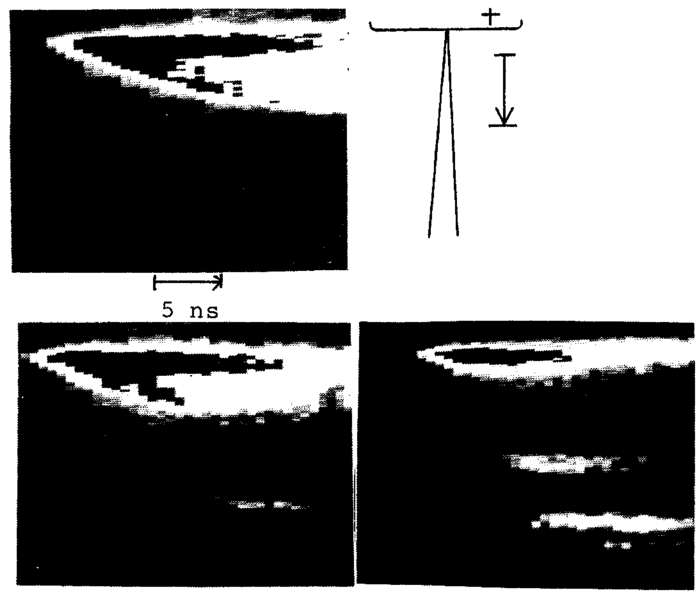

Figure 7. Streak photographs illustrating interaction of the incipient arc channel with the laser beam at moderately high laser energy in the Type 1 triggering geometry. In a) no voltage is applied to the gap, in b) 80% of self breakdown voltage, and in c) 98% of self breakdown voltage.

risetime associated with the spot formation, although the limits of our diagnostics may have been strained.

Conclusion

High sensitivity streak photography combined with fast spectroscopy, has provided direct evidence of the role of streamers in laser triggered breakdown, and of the interaction of the laser with the formative arc channel. The data acquired have provided greater insight into the operating mechanisms of laser triggered spark gap switches. The delay to breakdown in the laser triggered switch appears to be attributable to the sum of the time required for the streamer to traverse the gap, and the time necessary for heating the streamer trail, allowing full current conduction. The small diameter of the initial ionization path probably contributes to the rapid heating of the channel, not requiring the constriction of the channel as in overvolted breakdown. The most probable form of interaction of the laser with the streamer is a cascade ionization process, in which the free electrons at the leading edge of the streamer absorb energy from the laser beam and ionize nearby atoms or molecules,

effectively enhancing the ionization coefficient relative to the case with no laser beam. It is anticipated that an infrared laser may be preferable to a visible laser to enhance the streamer velocity in this manner since the efficiency of a cascade ionization process is inversely proportional to optical frequency. No measurements were performed on a laser triggered gap illuminated with visible or ultraviolet radiation. Significantly different modes of ionization may be important in those cases.

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